

Dearborn, Michigan
NOISE-CON 2008
2008 July 28-30

Measured rattle threshold of residential house windows

Natalia Sizov^a
Troy Schultz^b
Christopher Hobbs^c
Wyle Laboratories
241 18th Street, Suite 701
Arlington, VA 22202-3419

Jacob Klos^d
NASA Langley Research Center
2 North Dryden Street
MS 463, Bldg 1208, Rm 115
Hampton, VA 23681-2199

ABSTRACT

Window rattle is a common indoor noise effect in houses exposed to low frequency noise from such sources as railroads, blast noise and sonic boom. Human perception of rattle can be negative that is a motivating factor of the current research effort to study sonic boom induced window rattle. A rattle study has been conducted on residential houses containing windows of different construction at a variety of geographic locations within the United States. Windows in these houses were excited by a portable, high-powered loudspeaker and enclosure specifically designed to be mounted on the house exterior to cover an entire window. Window vibration was measured with accelerometers placed on different window components. Reference microphones were also placed inside the house and inside of the loudspeaker box. Swept sine excitation was used to identify the vibration threshold at which the response of the structure becomes non-linear and begins to rattle. Initial results from this study are presented and discussed. Future efforts will continue to explore the rattle occurrence in windows of residential houses exposed to sonic booms.

1. INTRODUCTION

Current Federal Aviation Administration regulations prohibit commercial supersonic flights over US land and restrict military flights to high altitudes or specially designated airspaces. Such regulations are required because sonic booms from existing aircraft are found to be unacceptable by the public. Shaping an airframe can reduce the loudness of booms heard outdoors¹. There are, however, additional effects inside of the house that contribute to overall disturbance. According to past surveys², rattle is one of the most annoying factors for people experiencing sonic booms indoors.

^a Email address: natalia.sizov@wyle.com

^b Email address: troy.schultz@wyle.com

^c Email address: chris.hobbs@wyle.com

^d Email address: j.klos@nasa.gov

This current effort expands upon related rattle studies conducted in the mid 1960's³. During past studies the threshold excitation level was found in terms of the exterior sound pressure level^{3,4}, or the acceleration levels of walls and other building elements⁵. During an experimental study of the rattle of wall-hung mirror carried out by Carden and Mayes⁶ a sinusoidal excitation was applied at wall resonance frequency of 15 Hz. Several past rattle studies have utilized different acoustical excitation sources such as steady state sound⁷ or vibration, aircraft noise, blast noise and other impulsive noises, which are dominated by low-frequency content⁸. The development of rattle prediction models based on these data was initially attempted to model the acceleration level for the threshold of rattle of wall-hung objects and objects on horizontal surfaces⁹. Early publications found a wide range of rattle threshold values which varied between 0.01g⁴ to 1g⁹ depending on material, sizes, age, outdoor overpressure, frequency and method of study.

The current paper presents initial results of a NASA sponsored project to study window rattle mechanisms, and to model the rattle occurrence caused by sonic boom excitation. The foundation of this research is the collection of vibroacoustic response data on a wide variety of windows in existing residential houses. A focus of this work to date was the experimental determination of rattle threshold of the different windows. This paper describes the methods used and some initial findings.

2. RATTLE THRESHOLD MEASUREMENTS

More than 40 windows were tested for their response to airborne low-frequency sound. These included windows of different types, material, and sizes in houses of different constructions. Windows were located in houses near airports in New Hampshire, Virginia and Pennsylvania. The owners of these houses were participating in FAA sponsored sound insulation program. Wyle's involvement with this sound insulation program made these windows available for the research that is the focus of this paper. Shortly after the rattle experiments reported in this paper the tested windows were removed and replaced with new windows. Some of the removed windows were retained for future laboratory tests.

A new portable sonic boom simulator was built to study the vibration of windows exposed to sonic booms and other types of acoustic excitations (Figure 1). It consists of two connected modules, a small 0.9x0.3x0.6 m module and a large 1.4x1.2x0.5 m module. The small module has an open back and contains two 15" full range JBL 2226 speakers. The simulator was made of 12 mm-thick Baltic birch and weighs less than 200 pounds. The simulator was placed outside of the house, covering the tested window and was pressed firmly against the wall. When in position the large module forms an enclosed acoustic cavity between the speakers and the exterior surface of the window. The large module is lined with poly-foam to damp the acoustic resonances of the air cavity and increase the spatial uniformity of the sound field acting on the window. The simulator is capable of generating a sound level above 140 dB (4 psf). Transient and steady state excitations were studied, and results for sinusoidal excitations are presented here.

Accelerometers were mounted to the windows and house walls at various locations. Lightweight PCB model 353B17 and Endevco model 2250A-10 accelerometers, with 10 mV/g sensitivities, were used on structural elements where mass loading was a concern. For structural elements where mass loading was not a concern, PCB model 356A27 accelerometers with 100mV/g sensitivity were used. Accelerometers were placed on the interior glass, sash, and frame of all tested windows. As an example, Figure 2 shows accelerometer mounting positions for one of the double-hung wooden frame window. Accelerometers were placed on the:

- low corner of upper glass panel (channel 3),
- middle of upper glass panel (channel 4),

- center of upper glass panel, low level (channel 5),
- upper frame middle (channel 6),
- upper corner of upper sash (channel 7),
- center of upper horizontal sash of the low panel (channel 8), and
- middle of left vertical sash of upper panel (channel 9).

To measure the acoustic excitation and response, Brüel and Kjær Type 4193 low frequency microphones were placed at the three locations:

- inside the large module of the simulator (channel 10),
- inside the house in the room where the window was located (channel 11), and
- outside the house behind the speaker (channel 12).

Response data were recorded on a National Instruments 24-bit digital recording system at a sample rate of 96 kHz.

The rattle threshold of the windows was determined by exciting them acoustically using amplitude swept sinusoidal signals at discrete frequencies ranging from 10 to 500 Hz. The excitation was produced using a signal generator, the output of which was passed through an amplifier to drive the speakers of the simulator. To create the amplitude sweep the signal generator's output voltage was gradually increased by an operator. Figure 3 shows an example of the sound pressure measured inside the simulator for a manual amplitude sweep of a 50 Hz tone. As the test was performed the sound pressure level measured by a microphone placed inside the simulator varied from low level to a maximum level of 189 Pa (140 dB, or 4 psf), then back to low level. For improved repeatability, the procedure was eventually improved to use computer-generated signals instead of manual manipulation of a signal generator's output level.



Figure 1: Sonic boom simulator

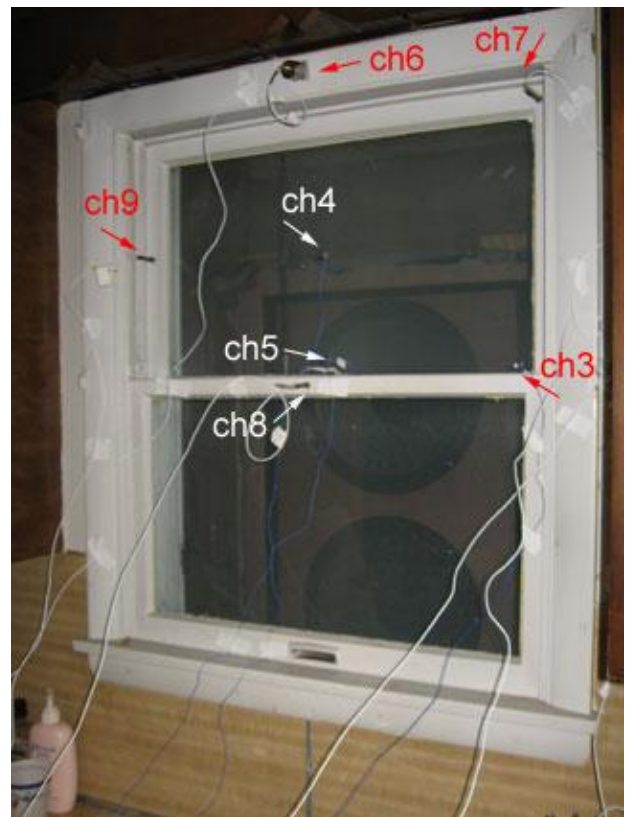


Figure 2: Accelerometer position inside the house (house #226, window W6)

3. RESULTS

Figures 4 through 6 and 8 show portions of the recorded time history of an accelerometer, channel 8, which is located at the center of the upper horizontal sash of the lower windowpane (Figure 2). These data are for window W6 in a house # 226. During this test rattle first occurred at 3.4 seconds at an acceleration level of about 1.5 m/s^2 . On Figure 4 points where rattle first occurred are marked by arrows. The rattle continued as the amplitude was increased. The sound pressure level reached the maximum 19 seconds into the test (Figure 3), which produced very high acceleration levels and significant rattle (Figure 5). As the excitation amplitude was decreased, rattle subsided 34 seconds into the test at an acceleration level of approximately 1.5 m/s^2 (Figure 6).

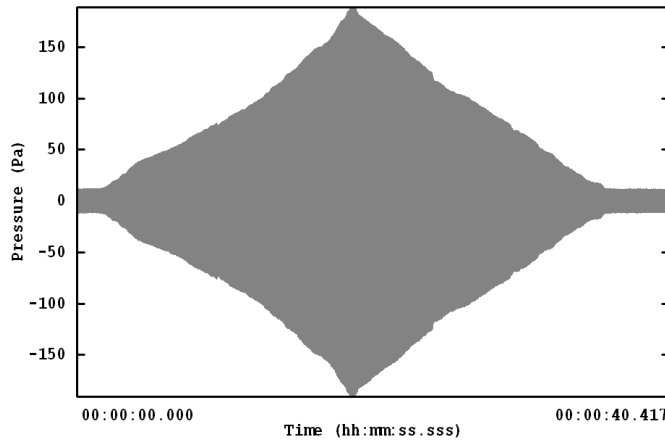


Figure 3: Outside pressure amplitude (50 Hz, channel 10, house # 226, window W6)

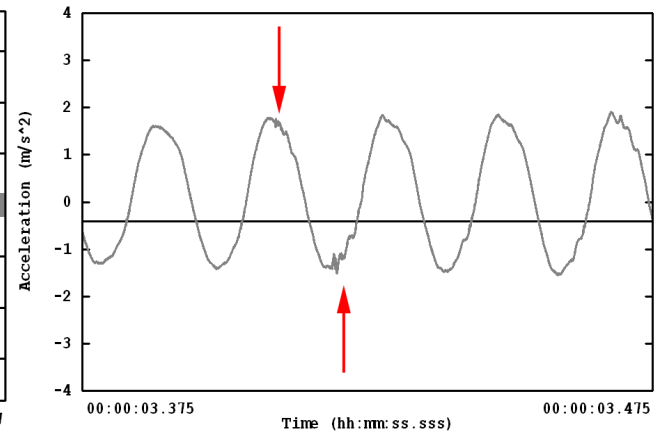


Figure 4: Time history of acceleration, rattle onset (50 Hz, channel 8, house # 226, window W6)

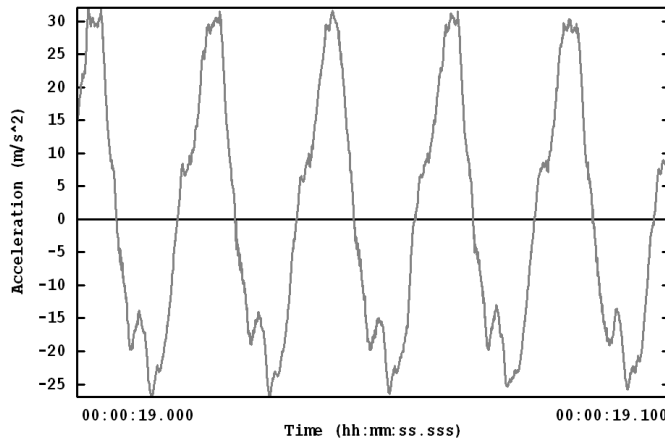


Figure 5: Acceleration time history, at the maximum excitation (50 Hz, channel 8, house # 226, window W6)

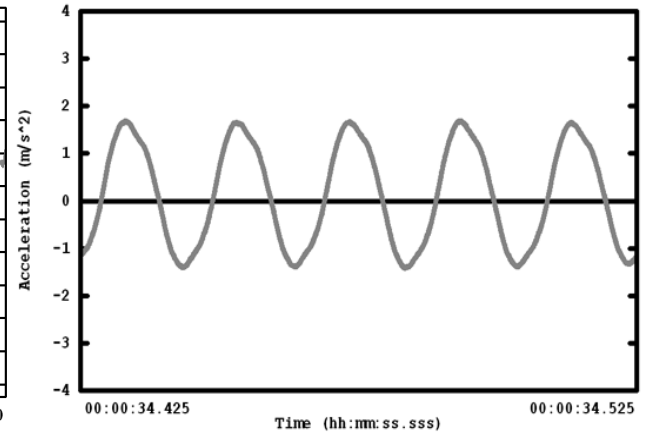


Figure 6: Time history of acceleration, rattle cessation (50 Hz, channel 8, house # 226, window W6)

These test demonstrate that contact induced vibration is not present at low excitation levels and the window responds sinusoidally to a sinusoidal excitation. As the excitation level increases and rattle begins, the window response begins to exhibits non-linear behavior. The excitation level first causing contact induced vibration is defined as the rattle onset threshold. Once this threshold is exceeded, contact induced vibration became evident in the measured responses and the rattle noise became audible indoors. The point when rattle cased- rattle offset- was also identified from time domain responses.

Inspection of the time domain responses is labor intensive. Given the large number of windows that must be analyzed, other methods to quickly identify rattle onset and offset were sought. When contact induced vibration is present in the window the response of the window to a sinusoidal input is not sinusoidal. In the spectral domain, these nonlinearities in the window response will appear as harmonics of the fundamental excitation tone. Mapping the amplitude of the fundamental and the harmonics has proven useful in identifying the onset and offset of rattle.

The spectrogram of the time history from channel 8 is shown in Figure 7. Fundamental and higher order harmonics are distinguishable. Changes in the Power Spectral Density (PSD) of higher order harmonics are visible as the vertical lines occurring at about 3, 8, 12, 30 and 34 seconds. The effects associated with these times are best understood by examining the time histories. As it was noted above, the time of 3.4 seconds corresponds to rattle onset, and the time of 34 seconds corresponds to rattle offset. There are multiple thresholds of the window, for example, figure 8 illustrates how the rattle increases in intensity as the excitation level increases 12 seconds into the test.

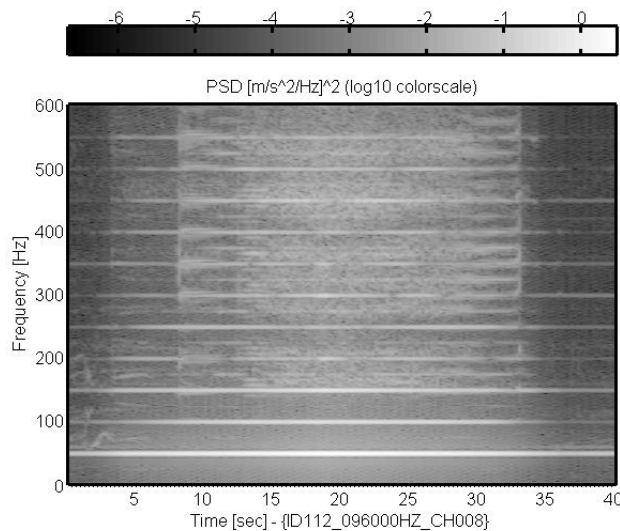


Figure 7: Spectrogram
(50 Hz, channel 8, house # 226, window W6)

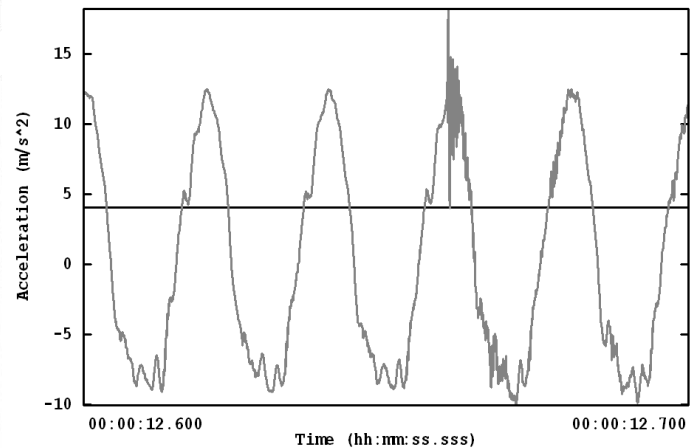


Figure 8: Time history of acceleration, at 12 seconds
(50 Hz, channel 8, house # 226, window W6)

The increase in the amplitude of the power spectrum at the fundamental frequency as test progressed is shown in Figure 9. On Figures 10 through 12 the amplitude of the fundamental harmonic is shown on the abscissas, and the amplitude ratio of higher order harmonics to the fundamental is shown on the ordinates. Two curves are presented, one for the case when the excitation level was increasing and one for the case when it was decreasing. When the fundamental reached a certain level the relative amplitude of higher order harmonics began to increase rapidly (Figure 10 and 12). Nonlinear vibration causes this rapid increase in the amplitude ratio, and this rapid increase can be used as an indicator of rattle onset. For example, in Figures 10, 11 and 12 a rapid increase began when the fundamental PSD amplitude was approximately $0.3 \text{ m}^2/(\text{s}^4\text{-Hz})$. Referring back to Figure 9, the time at which the fundamental harmonic reached an amplitude of $0.3 \text{ m}^2/(\text{s}^4\text{-Hz})$ was between 3 and 4 seconds into the test. This time was previously identified as the moment of rattle onset based on the time history shown in Figure 4 and the spectrogram shown in Figure 7. Thus, a quantitative measure of rattle onset can

be developed from the experimental data by comparing the relative amplitude of the higher order harmonics to the amplitude of the fundamental.

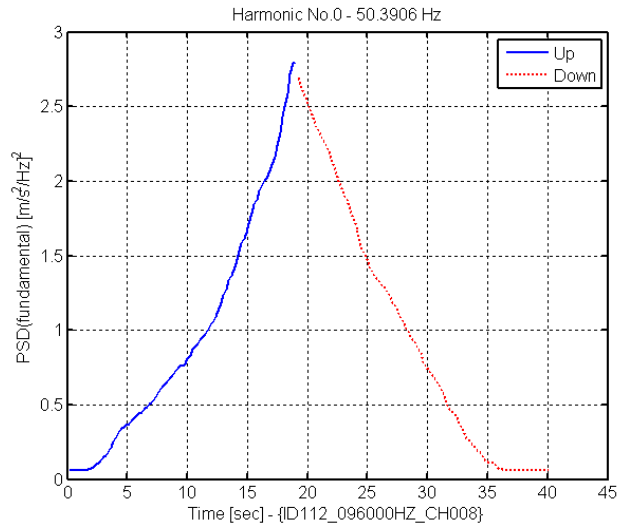


Figure 9: Fundamental harmonic time history, (50 Hz, channel 8, house # 226, window W6)

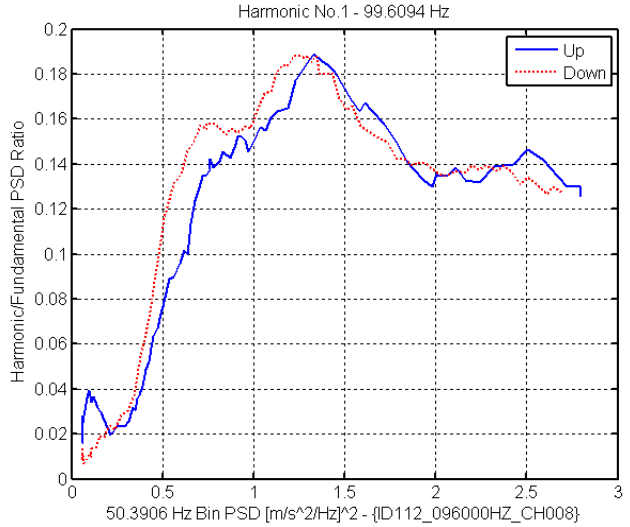


Figure 10: Ratio of first harmonic PSD vs fundamental harmonic PSD, (channel 8, house # 226, window W6)

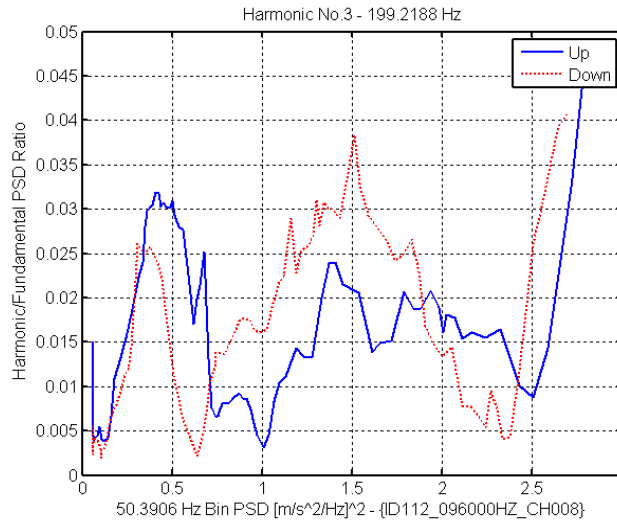


Figure 11: Ratio of third harmonic PSD vs fundamental harmonic PSD, (channel 8, house # 226, window W6)

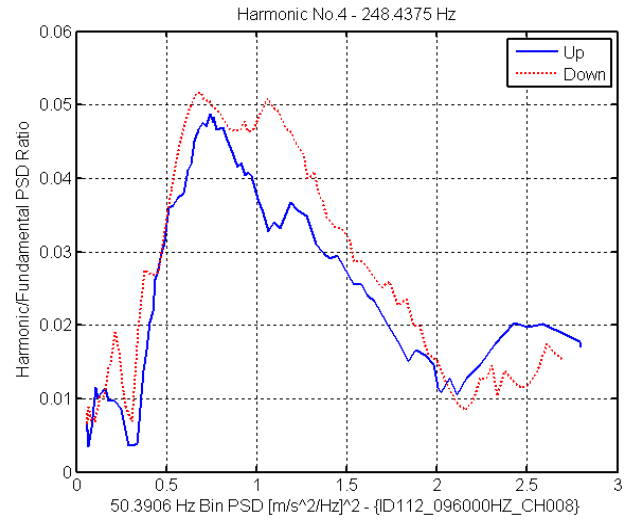


Figure 12: Ratio of forth harmonic PSD vs fundamental harmonic PSD, (channel 8, house # 226, window W6)

From Figures 10 and 11 it is seen that another dramatic increase in the amplitude of the higher order harmonics relative to the fundamental occurred when the fundamental reaches an amplitude of $1 \text{ m}^2/(\text{s}^4 \cdot \text{Hz})$. This corresponds to a time of 12 seconds in Figure 9, and also appears as vertical line in the spectrogram (Figure 7).

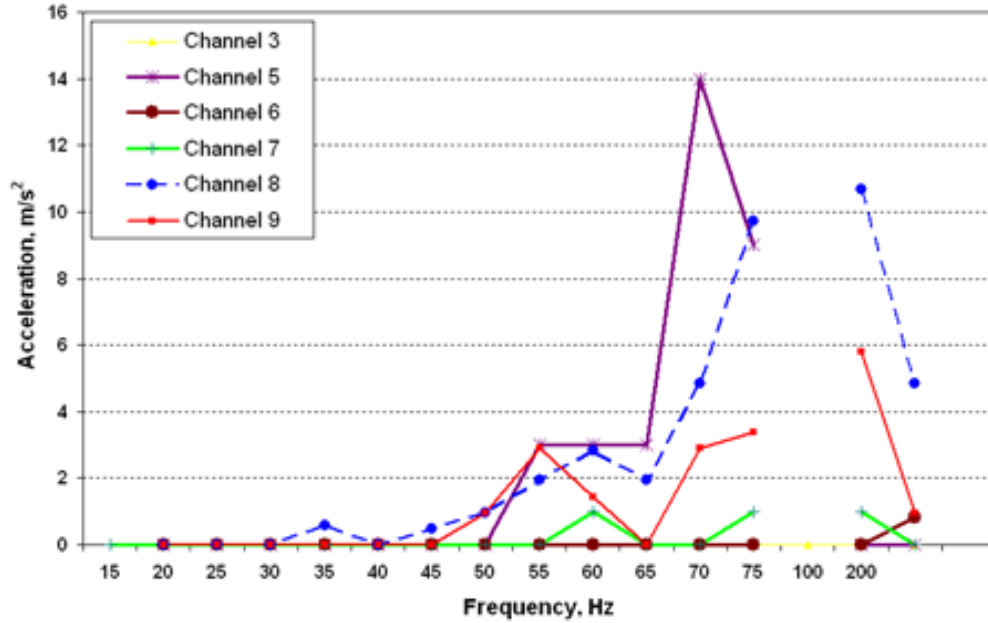


Figure 13: Rattle threshold for different window elements (house # 226, window W6)

From Figures 10, 11, and 12 that the excitation amplitude which induces a change in the state of rattle is different depending on whether the excitation amplitude is increasing or decreasing. For example, the moment of rattle onset corresponded to an excitation level of approximately 36 Pa (125 dB, or 0.77 psf). As the amplitude of the excitation was decreasing, the rattle offset corresponded to an excitation pressure in the enclosure of 27 Pa (123 dB, or 0.57 psf). There are two possible causes of this behavior. It is possible that less energy is required to sustain rattle when the excitation amplitude is decreasing. Another possible cause of this is the window components that are rattling may have displaced to a new position which has a different rattle threshold.

The rattle threshold, or the excitation level which causes the onset of rattle, varied depending on which window element was analyzed. The resulting temporal acceleration responses also had different patterns depending on the locations of the accelerometer. For example, the middle of the glass panel tended to exhibit a clear sinusoidal response and contact was not detected until very high excitation levels. For some windows rattle was not detected at all in the windowpane. For other parts of the window contact was detected at much lower excitation levels. In window corner non-linear response was recorded during the entire measurement duration starting immediately at the beginning. Figure 13 shows the threshold estimates for different window parts from house # 226. Here and in Figure 14 the ordinate indicates the acceleration level when rattle was first detected during each amplitude swept sine test and the abscissa indicates the fundamental excitation frequency. No measurements were taken at 70 or 80 Hz for this window. The channels indicated in the legend of Figure 13 correspond to the accelerometer locations shown in Figure 2. At low frequencies, below 45 Hz, rattle was present when test just initiated and threshold estimates at these frequencies are indicated here by zeros (Figure 13 and 14). It can be seen from these data that the threshold at which rattle detected varied significantly from element to element.

A database of responses from more than 40 windows was collected. Some windows had storm windows and some had screens. The presence of those affected the measured vibration response. It was found that when window has a storm or a screen its rattle threshold is higher.

It should be noted that rattle threshold also varied from house to house. Figure 14 gives examples of threshold acceleration level for three double hung windows located in two different houses and variations in the threshold can be seen. At the house # 208, the window was tested with and without storm window in place. At the house #226 the window was tested with and without the screen in place. Channel 8 was always located in the position illustrated in Figure 2. Channel 5 was positioned just above it on the windowpane (Figure 2). The threshold is frequency dependent at low frequencies small acceleration levels induced rattle. A local maximum is found around 60-100 Hz, which is consistent with other earlier findings⁹. This would indicate that higher acceleration levels are required to induce rattle at these frequencies.

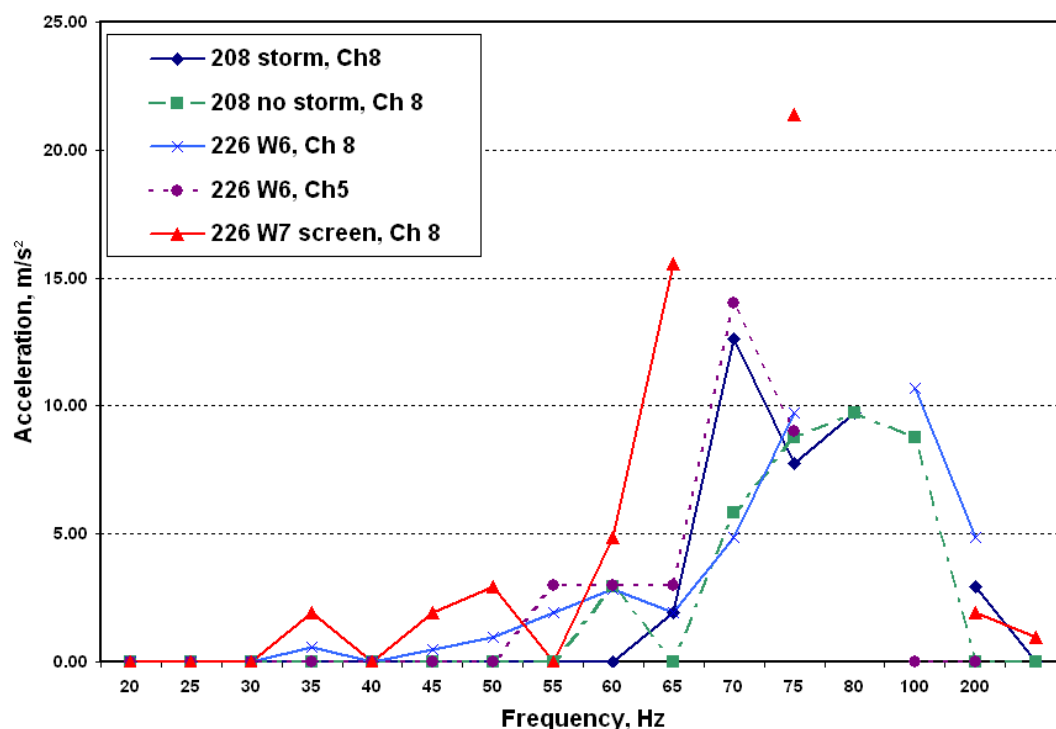


Figure 14: Rattle threshold for different houses, measured on frames (Channel 8) and glass (Channel 5).

4. CONCLUSIONS

This paper describes an experimental methodology that was used to determine the rattle threshold of residential house windows by subjecting them to sinusoidal acoustic excitation. For this testing a portable excitation device was built that mounts to the outside of the house. The method is based on experimentally detecting the onset of rattle while gradually increasing amplitude of a pure tone excitation. The technique was used on many windows located in houses that are part of an FAA sponsored noise insulation program. Inspection of the time domain and spectral analysis are used to predict rattle onset and offset. From the analyses of the large numbers of windows tested, it was demonstrated that different threshold levels are found in different houses, different windows at the same house and the same window with and without screen or storm windows. It was also shown how different window parts exhibit different

threshold levels. These conclusions illustrate that a range of rattle thresholds can be expected over the variety of houses that may be exposed to sonic booms if supersonic overland flight were allowed.

Results of this study will be used in further investigation of rattle mechanisms and the development of tools for predicting rattle response of windows exposed to sonic booms.

ACKNOWLEDGMENTS

This work was funded by NASA Langley Research Center, Contract number NNL05AA04Z.

REFERENCES

- ¹ Buehrle, R.D., Klos, J., Sullivan, B.M., and Haering, E.A.. Jr., "Building structural acoustic response to aircraft sonic booms," Paper 2pPA5, 4th Joint Meeting of the Acoustical Society of American and the Acoustical Society of Japan, November 2006.
- ² Borsky, P.N., "Community Reactions to Sonic Booms in the Oklahoma City Area", National Opinion Res. Ctr., AMRL Rept. TR-65-37, Repts. I and II, 1965.
- ³ Hubbard, H.H., and Mayes, W.H. "Sonic Boom Effects on People and Structures," in Sonic Boom Effects, Seebass, A.R. (ed.), NASA SP-147, NASA- Langley Research Center, 65-76, 1967.
- ⁴ Toshinya Kitamura, Jun-ichi Takano, Yosuke Imura, Shinji Yamada, "Threshold of Rattling of Windows and Doors by Low Frequency Noise", Journal of Low Frequency Noise, Vibration and Active Control, v.19, No. 3, Sept. 2000.
- ⁵ Sutherland, L.C. and Czech J, "Evaluation of Human Response to Structural Vibrations Induced by Sonic Booms," Wyle Research Report, May 1992.
- ⁶ Carden H.D. and Mayes W.H., "Measured Vibration Response Characteristics of Four Residential Structures Excited by Mechanical and Acoustical Loadings," NASA TN-D-5776, NASA- Langley Research Center, April 1970.
- ⁷ Nakamura, S., and Tokita, Y., "Frequency characteristic of subjective responses to low-frequency sound," Proc., INTER-NOISE 81, pp. 735-742, 1981.
- ⁸ "Findings of the Low-Frequency Noise Expert Panel of the Richfield-MAC Noise Mitigation Agreement of 17 December 1998," September 2000.
- ⁹ Clevenson, S.A., "Experimental Determination of the Rattle of Simple Models," NASA TM 78756, NASA- Langley Research Center, July 1978.